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SPACE RADIATION ENVIRONMENTS FOR PARTS SELECTION/TEST CONSIDERATIONS IN TYPICAL SATELLITE ORBITS

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14. ABSTRACT

This document contains the results of a space radiation environment study that can be the basis for parts selection and radiation tradeoff architectures for several typical spacecraft orbits used (or contemplated for use) by DoD and other government agencies. The radiation levels calculated can be used to select and test components for many spaceflight systems and subsystems. This report provides the first step in developing a comprehensive test program plan to examine all deleterious space effects that could degrade or disrupt sensor systems from meeting their mission goals regarding both performance and lifetime. The radiation levels recommended in this report represent a reasonable near worst case environment for all of near-Earth space out to geosynchronous altitudes. The recommended levels are such as to have low risk for mission lifetime without providing an overly cautious approach that could reduce program flexibility in the selection of components and inflate costs beyond program budget constraints.

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1. INTRODUCTION

This document contains the results of a space radiation environment study that can be the basis for parts selection and radiation tradeoff architectures for several typical spacecraft orbits used (or contemplated for use) by DoD and other government agencies. The radiation levels calculated can be used to select and test components for many spaceflight systems and subsystems. This report provides the first step in developing a comprehensive test program plan to examine all deleterious space effects that could degrade or disrupt sensor systems from meeting their mission goals regarding both performance and lifetime. The radiation levels recommended in this report represent a reasonable near worst case environment for all of near-Earth space out to geosynchronous altitudes. The recommended levels are such as to have low risk for mission lifetime without providing an overly cautious approach that could reduce program flexibility in the selection of components and inflate costs beyond program budget constraints.

The radiation levels calculated include for radiation dose, both the total dose to be considered and a minimum and maximum dose rate to be used to achieve the total dose that would bracket the conditions for all potential orbits. The dose rate also brackets, within reason, an expected rate to be seen at the component level on orbit. Dose rate is especially important as it relates to Enhanced Low Dose Rate Sensitivity (ELDRS) degradation of advanced bipolar technology components. Single Event Effect (SEE) levels are such that Single Event Latchup (SEL) is precluded for any and all cases that could cause program termination. Single Event Upset (SEU) levels and even some non-destructive SEL levels that can be reset will be evaluated for testing based on the free space cosmic ray background, the proton background in the heart of the high energy proton belt, and a worst case composite solar particle event.

The program radiation level test requirements contained in this document were determined from a number of typical and worst case orbits. Orbits evaluated included, but were not limited to:

- a 98.8° circular polar orbit at 830 km,
- a 0° inclination circular orbit through the heart of the inner proton belt at ~3500 km,
- a 0° inclination circular orbit through the slot region at ~7600 km following a major high energy electron injection event,
- a 0° inclination circular orbit through the heart of the quiet outer electron belt at ~19,000 km,
- a GPS orbit at 55° inclination and approximately 20,000 km ,
- a 0° inclination geosynchronous orbit at ~36,000 km,
- a 0° inclination geosynchronous transfer orbit from ~350 km to ~36,000 km, and
- a 63° Molynia orbit with an ~ 900 km perigee and 40,000 km apogee.

The key elements for determining a radiation test program plan are:

- Projected total dose levels and dose rates.
- Parts relative dose hardness, and SEE susceptibility criteria.
- Projected proton and heavy ion environments, and linear energy transfer (LET) levels for single event effects.

Other factors such as spacecraft charging, both surface and deep dielectric, may need to be considered, but are not included in this report. Similarly, dose contamination by lower energy (keV) particles of optical coatings or surfaces may need to be considered since specific mission sensors are also not included in this report.

Total-dose, orbit-specific environments and hardness assurance requirements for electronic components are presented in Section 2. Table 1 gives an orbit-dependent table of expected dose in rads (si) / year for various shielding thicknesses, as well as average, maximum and minimum dose rates in rads (si) / sec that should be considered. Recommended total dose test levels and rates at the device level are also given. Single event effects environments and criteria are described in Section 3. The recommended SEE environment to be considered for test at the device level is also given in Section 3. A partial list of references on the models and measurements used to determine the radiation environment and test procedures is included as Appendix A. Appendix B contains an edited copy of a "Radiation Considerations for a LEO Satellite Architecture Study". The study gives radiation trade options for selecting low altitude satellite orbits.

2. TOTAL DOSE

2.1 Radiation Environment

The total dose radiation environment that a spacecraft experiences is to first order a function of orbit selection, as the particle environments that produce the dose change from primarily protons in the inner belt region to primarily electrons through the heart of the outer belt region. At higher altitudes such as geosynchronous, electrons also dominate the dose for most of the year, but during major solar particle events, enhanced electron and proton backgrounds can produce the same dose levels in a few days that the satellite would normally see in months. Figure 1 below shows the "quiet" near-Earth radiation environment as measured/modeled behind approximately ¼ inch aluminum from the Combined Release and Radiation Effects Satellite (CRRES). The term "quiet" is used because no major particle injection events occurred during this period to enhance and change what is considered the steady-state background configuration of the belts.

Table 1. Orbit Radiation

Orbit Name	APOGEE (km)	PERIGEE (km)	INCLINATION (degrees)		Shielding Thickness			
					82 MILS	232.5 MILS	457.5 MILS	886.5 MILS
DMSP / LEO	830	830	98.8	TOTAL DOSE (krad/year)	2.30	0.83	0.65	0.46
				DOSE RATE (rads/sec)	7.3E-05	2.6E-05	2.1E-05	1.5E-05
GLOBALSTAR	1,410	1,410	55	TOTAL DOSE (krad/year)	12	7.28	6.52	4.55
				DOSE RATE (rads/sec)	3.7E-04	2.3E-04	2.1E-04	1.4E-04
INNER BELT PEAK	3,500	3,500	0	TOTAL DOSE (krad/year)	956	210	110	60
				DOSE RATE (rads/sec)	3.0E-02	6.7E-03	3.5E-03	1.9E-03
SLOT WORST CASE	7,600	7,600	0	TOTAL DOSE (krad/year)	221	175	161	71
				DOSE RATE (rads/sec)	7.0E-03	5.5E-03	5.1E-03	2.3E-03
OUTER BELT PEAK (Slot Empty)	19,000	19,000	0	TOTAL DOSE (krad/year)	435	4.87	0.77	0.47
				DOSE RATE (rads/sec)	1.4E-02	1.5E-04	2.4E-05	1.5E-05
OUTER BELT PEAK (Slot Full)	19,000	19,000	0	TOTAL DOSE (krad/year)	1915	34	3.69	1.66
				DOSE RATE (rads/sec)	6.1E-02	1.1E-03	1.2E-04	5.3E-05
GPS (Slot Empty)	20,000	20,000	55	TOTAL DOSE (krad/year)	116	1.03	0.24	0.14
				DOSE RATE (rads/sec)	3.7E-03	3.3E-05	7.6E-06	4.4E-06
GPS (Slot Full)	20,000	20,000	55	TOTAL DOSE (krad/year)	418	6.40	0.86	0.37
				DOSE RATE (rads/sec)	1.3E-02	2.0E-04	2.7E-05	1.2E-05
GEOSYNCHRONOUS	36,000	36,000	0	TOTAL DOSE (krad/year)	17	0.86	0.24	0.05
				DOSE RATE (rads/sec)	5.4E-04	2.7E-05	7.6E-06	1.6E-06
GEOSYNCHRONOUS TRANSFER (s-empty)	36,000	350	18	TOTAL DOSE (krad/year)	113	5.73	3.03	1.72
				DOSE RATE (rads/sec)	3.6E-03	1.8E-04	9.6E-05	5.5E-05

Table 1. Orbit Radiation (Continued)

Orbit Name	APOGEE (km)	PERIGEE (km)	INCLINATION (degrees)		Shielding Thickness			
					82 MILS	232.5 MILS	457.5 MILS	886.5 MILS
MOLYNIA	40,000	900	63	TOTAL DOSE (krad/year) DOSE RATE (rads/sec)	12 3.8E-04	0.58 1.8E-05	0.26 8.2E-06	0.12 3.8E-06
DMSP / LEO	830	830	98.8	TOTAL DOSE (krad/year)	1.20	0.17	< 0.1	< 0.1
GEOSYNCHRONOUS	36,000	36,000	0	TOTAL DOSE (krad/year)	4.28	0.61	< 0.4	< 0.4
GEOSYNCHRONOUS TRANSFER (s-empty)	36,000	350	18	TOTAL DOSE (krad/year)	3.00	0.43	< 0.3	< 0.3
MOLYNIA	40,000	900	63	TOTAL DOSE (krad/year)	3.42	0.49	0.35	0.35

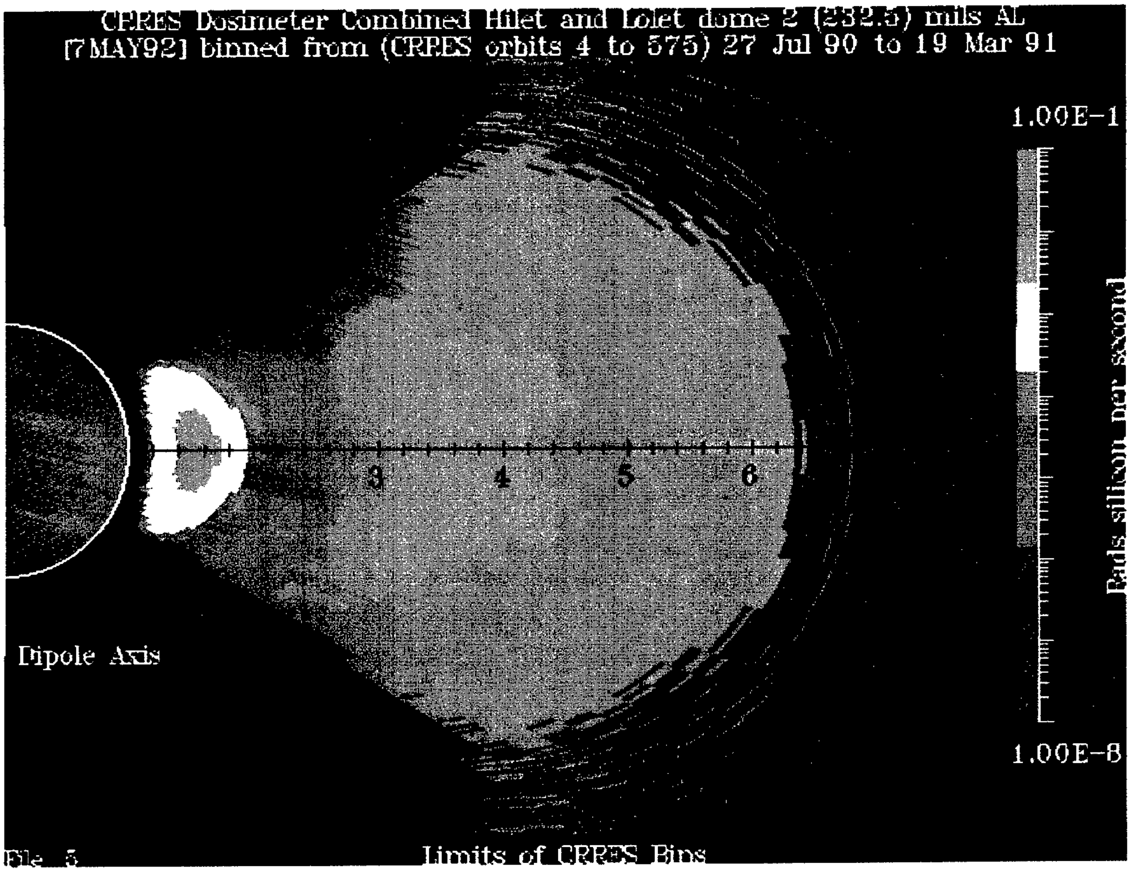

Figure 1. Quiet Near-Earth Radiation Dose Levels Behind ~1/4 inch Aluminum

The X-axis scale for Figure 1 is in Earth radii (R_E)starting from the center of the Earth. (1 R_E is at the Earth's surface.) Relative intensity of the dose levels is given by the logarithmic color scale. The figure is in magnetic coordinates to provide symmetry in data binning. The equator shown is the magnetic equator, which is 11° offset from the geographic equator. The inner belt center in red is nearly all proton dose from protons with energies greater than ~20 MeV. In steady state, this inner radiation belt of high energy protons extends from the top of the atmosphere in the region of the South Atlantic Anomaly to approximately 6500 to 7500 km. (1000 km = ~540 nautical miles)

Beyond approximately 9000 km outer belt MeV electrons start to provide a significant dose. The outer belt center in medium green is nearly all electron dose as is the geosynchronous environment at ~6.6 Earth radii (shown in blue). The dose for this shielding thickness is down approximately 2 orders of magnitude from the heart of the electron belt out to geosynchronous altitudes.

The region between the two belts is commonly termed the "slot region," since it is a region of minimum dose between the outer and inner peak radiation zones of the magnetosphere. However, and it's a big however, about once or twice per solar cycle (on average) a major space storm occurs that can produce an additional belt of energetic electrons and protons in this slot

region. This new belt produces more dose than in the heart of the inner belt for well-shielded (greater than ~1/2 inch aluminum equivalent) devices. Figure 2 below shows the belt configuration following the major space storm of March 91. The format is the same as Figure 1 for the radiation environment as measured/modeled behind approximately ¼ inch aluminum on CRRES.

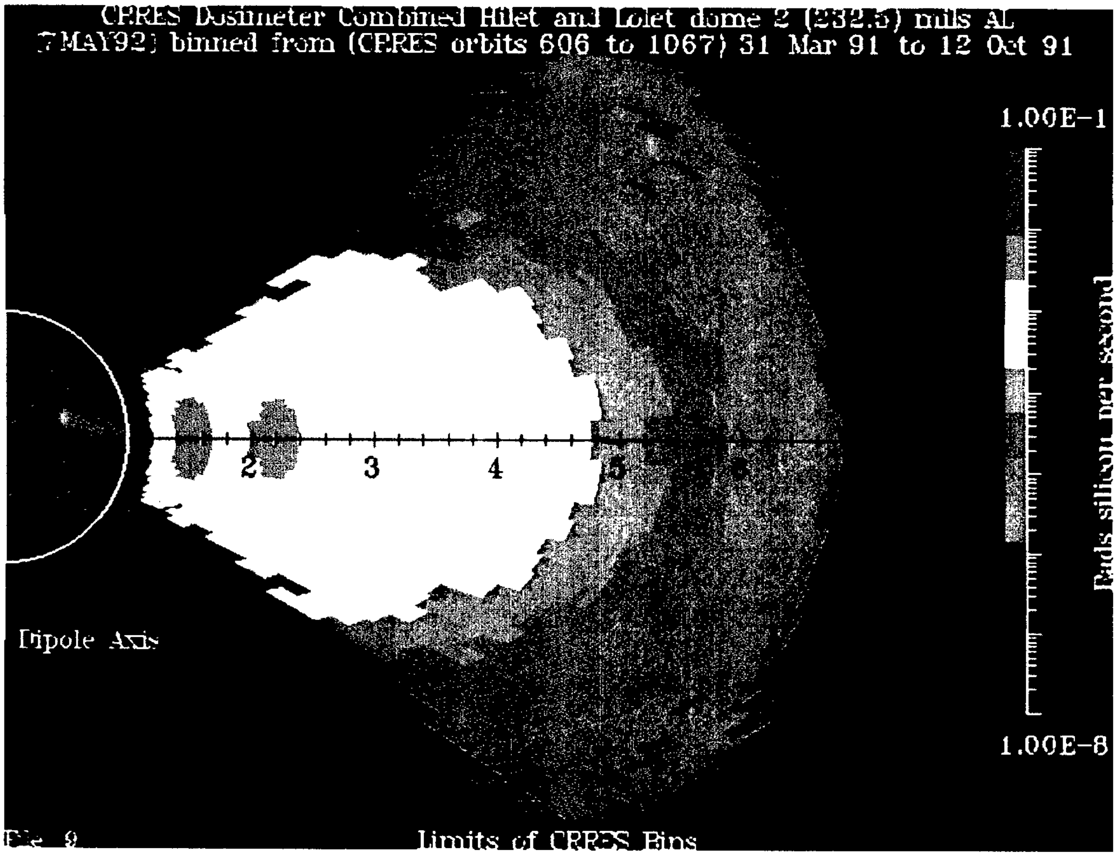

Figure 2. Major Storm-Enhanced Radiation Dose Levels Behind ~1/4 inch Aluminum

From Figure 2 it is evident that the slot region seen in Figure 1 has been filled in and is providing dose for this thickness shielding (within the precision of the color scales used) equivalent to that of the inner belt. It is also evident that this condition significantly enhances the dose through the outer belt all the way to geosynchronous altitudes. The cover Figure shows the relative intensities of the dose regions for shielding thicknesses greater than ½ inch aluminum, emphasizing the harsher environment in the former slot region in this particle configuration. (Note: The scales of Figure 2 and the cover are not the same absolute levels.) The probability that this belt configuration will exist at any given time is less than ~10 percent, but it is either there or it is not, and it needs to be considered for both total dose and dose rate implications.

2.2 Orbit Characteristics

Since at Shuttle altitudes (300 to 500 km) yearly dose is less than ~200 rads (si) per year behind ~80 mils aluminum shielding (the minimum recommended for any electronics components),

orbits below 500 km will not be considered in this plan. If an orbit in this altitude range is considered, a 300 rad total dose radiation test would give a 50 percent margin for a one year mission. With as little as 4 mils shielding, the dose level only reaches approximately 1 krad at the 500 km altitude. Thus, the plan will consider what might be termed "orbits of opportunity" for evaluating environment levels for developing test criteria. Radiation levels for each orbit considered are summarized in Table 1 at the end of Section 2.

2.2.1 Low Earth Orbit (LEO)

A number of LEO orbits such as that of the Defense Meteorological Satellite Program (DMSP) spacecraft (which have been flying since the 1970's in a 98.8^{o} inclination, circular polar orbit at an altitude of 830 km) have radiation environments that are both well-measured and well-modeled. The main radiation hazard for spacecraft in this orbit is energetic protons that are trapped in the Earth's inner radiation belt. Because of the offset of the Earth's magnetic field center from its geographic center, at 830 km these energetic protons are only seen in the region of the South Atlantic Anomaly (SAA).

For low-altitude, high-inclination orbits, other dose regions to be considered are the low-altitude horns of the outer electron radiation belt and the polar cap region where both cosmic rays and solar protons have their easiest access to low altitudes. Most dose from the outer zone electrons can be easily shielded away with as little as 80 mils equivalent aluminum. At altitudes below 3500 km, the outer zone electron dose is only important for very thinly shielded components. Here also, the low background cosmic ray level contributes only marginally to total dose. Major Solar Particle Events (SPE) though can contribute significantly to lightly shielded components. If a spacecraft traverses Low Earth Orbit (LEO) Polar Regions where it will be exposed to SPE particles, they are seen continuously through the life of a solar particle event (which could be days) at all times the satellite is in the Polar regions.

2.2.2 Globalstar Orbit

At slightly higher altitudes, commercial satellite constellations such as Globalstar (which contains 48 satellites in 1,410 km circular orbits at 52 degrees inclination) experience slightly higher radiation environments, but still predominantly from inner radiation belt protons.

2.2.3 Proton Inner Belt Worst Case Orbit

Continuing up, the peak of the inner belt is at approximately 3,500 km where the high energy proton dose maximizes. A 0 degree inclination orbit at this altitude will produce the average worst-case, high-energy-proton environment.

2.2.4 Slot Region Worst Case Orbit

The slot region following a major storm event is highly pumped up in energetic electrons greater than 10 MeV up to at least 30 MeV following these "on average" once or twice per solar cycle storms. [Solar Cycle is approximately 11 years.] Electrons of these energies are not shielded even with aluminum thicknesses greater than ½ inch. A 0 degree inclination orbit at an altitude

of approximately 7,600 km will give the average worst-case energetic electron dose in the filled slot region.

2.2.5 Electron Outer Belt Worst Case Orbit

Continuing up, the peak of the outer belt is at approximately 19,000 km where the steady state high energy electron dose maximizes. A 0 degree inclination orbit at this altitude will produce the average worst-case, high-energy-electron outer belt environment. Most of this dose can be effectively shielded as long as a weight penalty is not an issue.

2.2.6 Global Positioning Satellite (GPS) Orbit

The GPS constellation of satellites are in a 55 degree inclination orbit at approximately 20,000 km. They are slightly above the peak of the outer belt, but get less dose due to their high inclination orbit. Again the outer zone electron dose at this altitude can be significantly reduced with shielding.

2.2.7 Geosynchronous Orbit

At what is termed "geosynchronous" altitude, the orbit period of a satellite approximates the rotational period of the Earth, thus allowing a spacecraft to sit over the same geographic longitude. This makes geosynchronous altitude a very desirable location for communication satellites and high altitude weather surveillance platforms. Furthermore the ~36,000 km, 0 degree inclination orbit is rather benign except during major high energy solar particle events. It is far removed from the inner proton belt and sufficiently far removed from the peak of the outer electron belt to be well down in radiation dose levels.

2.2.8 Geosynchronous Transfer Orbit

Although not a popular orbit for operational spacecraft, the geosynchronous transfer orbit is often used for experimental and small satellite payloads that can be carried along and ejected from geosynchronous launch vehicles at relatively low cost. The orbit cuts through all the peaks and valleys of particle populations of near-Earth space and thus is a great orbit for radiation studies. The orbit is typically low inclination, but not 0 degrees. Here 18 degrees inclination from 350 km to 36,000 km will be used which is the approximate orbit of the CRRES spacecraft.

2.2.9 Molynia Orbit

A favorite orbit of the surveillance world is an orbit that spends much of its 12 hour period near an apogee of ~40,000 km, outside the major radiation regions of near-Earth space due to its 63 degree inclination. However, due to its low perigee of ~900 km, it must traverse the harshest radiation environments and therefore accumulates a moderate amount of total dose, but not as much as geosynchronous orbits. SEE susceptibility however is greater due to the frequent passes through the inner proton belt.

2.3 Orbit Radiation Level Table

The data in Table 1, the Orbit Radiation Table, comes primarily from the Air Force Research Laboratory's radiation models and data bases, although other models (such as the NASA models) and data bases (such as IMP) were also considered in determining the final dose values.

2.3.1 Data Base Sources

The radiation databases and models used to produce the numbers in this report come from the CRRES, the Advanced Photovoltaic and Electronics Experiment (APEX) satellite, the IMP 8 satellite and the DMSP F-7 spacecraft. CRRES flew between July 1990 and October 1991, near solar maximum. CRRES was in a low inclination, geosynchronous transfer orbit and thus sampled most of the severest radiation hazard regions of near-Earth space. In addition to measuring the space particles, CRRES also directly measured dose, dose rate, spacecraft charging levels, electronic upsets and degradation, and arcing in dielectric materials. Results from CRRES have been published in over 100 journal articles, and the CRRES models are used by more than 150 groups throughout the world.

The APEX satellite gathered dosimetry data between August 1994 and May 1996, a period just prior to solar minimum. It flew in a 70° inclination, 362 km perigee by 2544 km apogee orbit.

The IMP 8 spacecraft is a NASA spacecraft that has been gathering high energy proton data in interplanetary space for over 2 solar cycles. Here we are only concerned with the SPE data for protons > 30 MeV that contribute to dose levels for major solar particle events. Events were examined primarily for the 3 years near solar maximum when the events are more frequent and typically larger than at solar minimum.

Finally, the DMSP F-7 satellite gathered dosimetry data between December 1983 and October 1987 through a period of solar minimum. The DMSP satellite is in a 98° inclination, 840 km circular polar orbit. Since DMSP flew close to solar minimum, the radiation environment (except for the number of solar flares) experienced by DMSP should be a worst case for inner belt dose levels which are higher during solar minimum than solar maximum.

2.3.2 Dose Data Shielding Considerations

Shielding of devices to at least 80 mils equivalent aluminum thickness is a good rule of thumb to use since ~80 mils aluminum is the point where the depth dose curve for electrons goes from a very steeply falling curve to a more gradual fall off with increased shielding thickness. In general, high Z materials (such as tungsten or tantalum) are good for shielding electrons and secondary bremsstrahlung from outside the material itself when extra shielding is required. Low or medium Z materials are better for protons but require more volume. Care must be taken not to use high Z materials directly on active elements made of lower Z materials such as silicon since the energy absorbed by the higher Z material cannot end sharply at the interface and thus transfers additional energy to the low Z element (dose enhancement). When using high Z shielding material on low Z active elements, it is necessary to put low Z coatings on the shielding

material at the interface to inhibit energy absorbed in the high Z material from transferring into the device.

The shielding levels used in the tables in this report are for aluminum spherical shielding thicknesses of 82 mils, 232 mils, 457 mils and 886.5 mils (approximately a tenth, a quarter, a half and a full inch respectively). They are the thicknesses of the domes from the AFRL dosimeters used to make the data bases and the models. Interpolation is used to derive dose for intermediate shielding levels. The values will tend to be conservatively high between 82 and 232 mils, but close to accurate at the higher shielding levels due to the shape of the depth dose curves for particle penetration.

2.3.3 Data Discussion

Table 1 gives the total dose and dose rates for the selected orbits of study behind 4 shielding thicknesses. The dose is considered to be received from an omni-directional flux of high-energy particles entering a sphere with the sensitive element in the center of the sphere. Since the models used are empirical, based on flight data and not theory, the dose data include secondary effects such as scattering and bremsstrahlung within the shielding material.

The 10's of MeV electrons in the pumped slot region are the most difficult to shield. The high-energy protons in the heart of the proton belts are the next most difficult, and they are always there in large numbers. The Globalstar orbit is next as it spends a fair portion of its time in the inner belt proton region. For the typical spacecraft orbits (such as LEO, GPS, Geosynch, and Molynia) shielding is very effective, mainly because the dose is primarily from electrons below 5 MeV. For each of these orbits, in a non-pumped environment, the dose is only about 1 krad per year behind ¼ inch aluminum equivalent shielding, which most devices have inside a spacecraft.

Except for the absolute worst case orbit through the heart of the inner proton belt during all conditions and through the slot region and outer electron belt peak during pumped-up conditions (typically less than 10 percent of the time over a solar cycle), shielding at a level of approximately ¼ inch aluminum equivalent brings the yearly total dose under 10 krad for all typical satellite orbits for the trapped particle populations. Most devices are buried inside a spacecraft with other boxes around them which provide significant additional shielding when full ray tracing to determine dose at any point within a spacecraft is done.

2.3.4 Solar Particle Event (SPE) Considerations

Table 1 includes dose from SPEs that occurred during the periods that data were gathered to produce the models. Depending on the orbit, some orbit values would need to be increased if the number and intensity of SPEs were greater over the period of flight than the periods used in the models. To better understand the potential dose influence of SPEs, we will exam the long term IMP 8 data base as compared to the DMSP dosimeter data base for the solar particle event of 26 April 1984, the largest event in the DMSP dosimeter data base.

Figure 14 b of reference 11 shows the "depth dose spectra for a DMSP/F7 crossing of the north polar cap at the peak of the solar particle event of 26 April 1984." This was the largest of the

SPEs seen by the DMSP/F7 spacecraft for dose behind both 82 mils and 232 mils aluminum shielding. The dose behind the 82 mils thick dome was 1.2 rad (1 rad protons and 0.2 rads electrons) for a single pass through the north polar region, and the dose behind the 232 mils thick dome was 0.15 rads (almost entirely protons). The actual measured doses for the total event period (reference 12) were 72 rads and 9.5 rads behind the 82 mil and 232 mil hemispheres, respectively. Of these dose values, all 9.5 rads is proton dose for the thicker shield, but only ~ 60 rads is protons for the thinner shield, the other 12 rads being electrons. The IMP 8 > 30 MeV peak proton flux for the April 84 event was ~ 500 counts and the counts remained relatively high for 5 days.

Examining the IMP 8 data for the 3 years near the solar maximum, 1989-1991, we find 4 events which exceeded the April 84 event. These were in August 89, September 89, October 89 and March 91. The August 89, October 89 and March 91 SPEs all had >30 MeV proton flux counts of ~2000, 4 times the April 84 level with event times of 10 days, 10 days and 6 days respectively. The September 89 event had a peak count of 1000, twice the April level and a length of 4 days. Assuming the peak flux counts times the event duration are proportional to the dose received (reasonable if the spectra are relatively of the same hardness), we can determine what the dose would be for each event at the 840 km altitude. The August and October 89 events would be approximately 8 times the April 84 dose levels or 576 rads (480 rads protons and 96 rads electrons using the same ratio of protons to electrons as the April 94 event) and 76 rads behind the 82 mil and 232 mil hemispheres, respectively. Similarly, the March 91 event would give total doses of 346 rads and 46 rads, and the September 89 event would give total doses of 115 and 15 rads behind the two thicknesses. Adding the totals for these large events and doubling the result to get dose inside a sphere, gives a total dose of ~3.2 krads with 82 mils shielding and ~0.4 krads with 232 mils shielding.

7 smaller SPEs of some significance occurred over the same 3 year period. Their total contribution to dose was ~.4 krads and less than .1 krads for 82 and 232 mils shielding, respectively. Thus, the total dose for the 3 years (1989-1991) near solar maximum from SPEs would have been ~3.6 krads (3.0 krads from protons and .6 krads from electrons) inside a 82 mil thick sphere and 0.5 krads inside a 232 mil sphere over the 3 year projected mission lifetime. Since the 1989-1991 solar maximum was one of the largest ever recorded (the previous maximum only had 1 major SPE that was approximately the same level as the April 84 event), there is no reason to believe future maximums will be worse although they could be. Since we cannot yet predict solar events, their size nor duration, these levels are felt to be reasonable given past experience, and will be the numbers used for SPE dose in this study. (Remember that this is inside a sphere with no back shielding.) Thus, the average contribution to total dose from SPEs would be ~1.20 krad/year for 82 mil spherical shielding and ~0.17 krad/year for 232 mil spherical shielding for a satellite in a DMSP 830 km polar orbit during the 3 years around solar maximum. [It is noted that these are short lived events with a high dose rate over the event periods.]

For other than the DMSP 830 km orbit, the numbers are scaled as to the amount of time a spacecraft would encounter SPE particles versus the time a DMSP orbit spacecraft encounters SPE particles. In the DMSP spacecraft orbit used, SPE particles can be seen up to 28 percent of the orbit period (>65° Latitude). Thus, an orbit that sees the particles 100 percent of the time

(such as geosynchronous) would have 3.57 times the DMSP orbit dose. Table 2-2 gives the expected dose maximum that can be added to the values in Table 2-1 to properly consider an average 1989-1991 SPE solar maximum condition for those orbits significantly affected.

2.4 Total Dose Testing

For most components that require total dose testing, parts can be tested per Mil Std 883 Test Method 1019.4 between 1 and 100 rads/sec at a Cobalt 60 facility. Even at the highest total dose rate in Table 2-1 of ~2 megarads per year, the dose rate is only ~0.06 rads/sec, less than the recommended Co60 test rate of 1 to 100 rads/sec. However, recently there has been increased concern with Enhanced Low Dose Rate Sensitivity (ELDRS) in certain bipolar components. The concern has escalated to the point where some users require both low dose rate testing and displacement damage testing.

With respect to ELDRS, one mission assurance requirements (MAR) document states, "Linear bipolar parts shall be assumed to be ELDRS susceptible unless credible evidence indicates the contrary." The ELDRS issue is, in some cases, causing parts replacements in high reliability space systems. The exact cause of ELDRS is still not completely understood, but susceptibility is much higher in lateral transistor bipolar parts than vertical transistor bipolar parts.

As near as we have been able to find, the ELDRS issue came about with the introduction of advanced bipolar technologies, specifically, the introduction of the polysilicon emitter transistor (PET). A 1991 paper by Enlow et al (("Response of Advanced Bipolar Processes To Ionizing Radiation", IEEE Trans. On Nuclear Science, Vol. 38, No. 6, p. 1342, December 1991) stated that the worst-case degradation for PETs occurs at the lowest dose rate complicating hardness assurance testing procedures. Although the term "ELDRS" was not coined in that paper, the work became the baseline from which the term arose. To quote from the conclusions, "For advanced bipolar technologies, the MIL-STD-883B Test Method 1019.4 hardness assurance test may not represent a worst-case for space environments." Although published in 1991 and confirmed by test and analyses over the next 10 years, the findings were never seriously considered for space flight parts selection criteria until recently. The reason for this has not yet been uncovered. However, during the intervening years, parts sensitive to ELDRS degradation have been flown in a multitude of space systems with no dose related failures that we have been able to confirm.

In November 1997, a Microelectronics and Photonics Test Bed (MPTB) was launched on a spacecraft into a highly elliptical orbit. The experiment and results are described in a 1999 paper by Titus et al ("Enhanced Low Dose Rate Sensitivity (ELDRS) of Linear Circuits in a Space Environment," IEEE Trans. On Nuclear Science, Vol 48, No. 6, December 1999). The paper states, "The experiment described herein is the first verification/demonstration of ELDRS in space...." Figure 3 is a graphic summary of the results from one of the devices under test, a LM124 Op-Amp. It can be seen that one of the device parameters exhibits ELDRS type behavior. However, the device did not exhibit catastrophic death, but continued to operate at and above the 50 nA maximum specification limit stated in the paper. The paper and analysis leave many questions yet unanswered as to ELDRS in space.

The other related testing recently requested is Neutron (Non-Ionizing Energy Loss (NIEL)) testing for characterizing displacement damage effects in parts performance. The NIEL testing could be related to the ELDRS testing in that bipolar parts are more susceptible to radiation dose from protons than from electrons. A combination of Co60 and neutron testing may be used to simulate proton irradiation damage. Testing this way is more cost effective than using proton facilities and more facilities are available for testing.

Thus, given the recent interest in ELDRS and its associated test requirements for certain operational spacecraft systems, total dose testing beyond Mil Std 883 Test Method 1019.4 may be necessary.

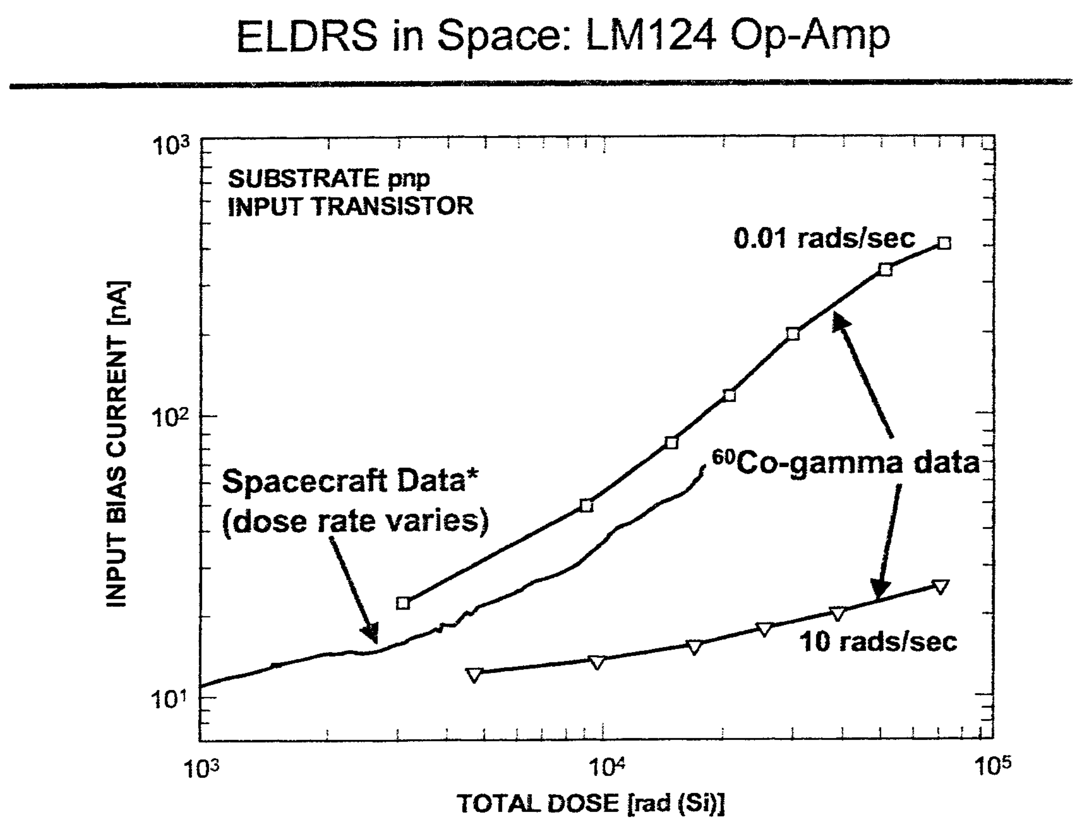

Figure 3. LM124 Flight Data Comparison To Ground Test Data

3. SINGLE EVENT EFFECTS

3.1 Effects Categorization

Single Event Effects (SEE) can be divided into two groups, those that can cause catastrophic failure of a system and those that only temporarily create a malfunctioning of the system. Devices that are vulnerable to non-recoverable or destructive Single Event Latchup (SEL), Single Event Burnout (SEB) and/or Single Event Gate Rupture (SEGR) should be avoided

whenever possible. Where a device with destructive SEE behavior is critical to the performance of the system, autonomous detection and correction circuitry must be part of the circuit design.

3.2 Acceptance Part Threshold Characteristics

Linear Energy Transfer (LET) threshold as defined by Ken LaBel of NASA/GSFC is "the minimum LET to cause an effect at a particle fluence of 1E7 ions/cm^2." (LaBel's Single Event Effect Criticality Analysis (SEECA) document can be found on the web at http://flick.gsfc.nasa.gov/radhome/papers/seecal.htm). LaBel requires a LET threshold of >100 MeV-cm^2/mg to preclude an environmental analysis. Others define LET threshold as simply "the minimum LET required to produce upset" or "the LET corresponding to a measured cross-section value". Hash et al from Sandia National Laboratories define Rad-Hard devices as those being immune to all SEEs at LET levels greater than 80 MeV-cm^2/mg. Devices with LET thresholds between 20-80 MeV-cm^2/mg are considered rad-tolerant but must be evaluated for latch-up risk. Devices with LET of less that 20 meV-cm^2/mg require a vulnerability assessment that should include device, circuit, type of SEE, SEE rate and mitigation technique effectiveness. Risk tradeoffs for any device with a LET threshold less than 20 MeV- cm^2/mg should be decided by the program parts control board.

3.3 Cosmic Ray and SPE LET Plots

In general, the cosmic ray background is cyclic in nature, varying inversely with solar activity [cosmic ray minima are in years of solar activity maxima (1990, 2001 projected)], although major solar magnetic storms can also decrease the background level during solar minimum. At times, the Sun produces bursts of protons and heavier ions during what are termed solar particle events (SPE). Upon reaching the Earth, these particles can produce energetic ion background levels that are thousands of times greater than the normal cosmic ray background level. Although SPEs occur more frequently during solar maximum, most of the proton flux is below 20 MeV which can be easily shielded from devices. Fortunately, SPEs with large fluxes of higher-energy particles (very hard spectrum) occur infrequently, usually only an average of 1 per year. Although 3 events which exceeded the April 84 event occurred in 1989, near the peak of the last solar cycle maximum, none occurred in 1990 and only 1 in 1991. Arguably, what is considered to be the most hazardous SPE measured to date, occurred in October 1989.

The galactic cosmic rays are the most constant source of SEEs. In this study no magnetic-cutoff is assumed, thus giving a worst case, and the most reasonable case since particles have nearly-direct-access to near-Earth space in high latitude and high altitude regions. The data come from the CHIME and CREME96 models. CHIME is the CRRES/SPACERAD Heavy Ion Model of the Environment for cosmic ray and solar particle effects on electronics in space.). The model covers the energy range from 10 MeV per nucleon to 60 GeV per nucleon for all stable elements, and includes the known major sources of heavy ions in the near-Earth region over this energy range: galactic cosmic rays, the anomalous component, and ions from solar energetic particle events. The model is discussed in detail in Chenette et al, IEEE Transactions on Nuclear Science, Vol. 41, No. 6, December 1994. The model outputs galactic cosmic ray spectra as a function of ion mass and energy, LET spectra, selected solar particle event spectra, and upset

rates for electronic devices if the cross section is input. It gives the output for a number of input parameters, to include orbit, shielding thickness and device thickness.

Galactic cosmic ray programs have been updated by two different groups, one from the USAF CRRES program which released a version called CHIME. Although CHIME came out of the CRRES program the major data base used was from the NASA IMP8 spacecraft. NRL in the same time frame made an updated version of CRÈME called CRÈME96 available on the web at http://creme96.nrl.navy.mil. *These two programs are compared with the objective of uncovering any differences that might impact the RIT program with respect to testing and experiencing SEEs. The main effort was to compare LET spectra at solar maximum, solar minimum and during a major SPE. The bottom line is that the two programs are remarkably close in their computations of the galactic cosmic background. They also behave similarly in free space handling of SPEs.*

The cosmic ray LET spectra for ions from the CHIME and CREME96 models were obtained for both solar minimum and solar maximum. The years of 1977 and 1990 were used as solar minimum and maximum respectively because those were the years used in CREME96. Plots of these values are shown in Figure 4. Here we see that for both solar max and solar min, the two sets of spectra agree remarkably well. The CHIME spectra seem a little harder at solar minimum but once shielding is added (Figure 5), it is hard to distinguish between spectra. Figure 5 is the solar min spectra behind 100 mils aluminum shielding. These are the recommended LET values for determining cosmic ray upset levels from device cross-section testing.

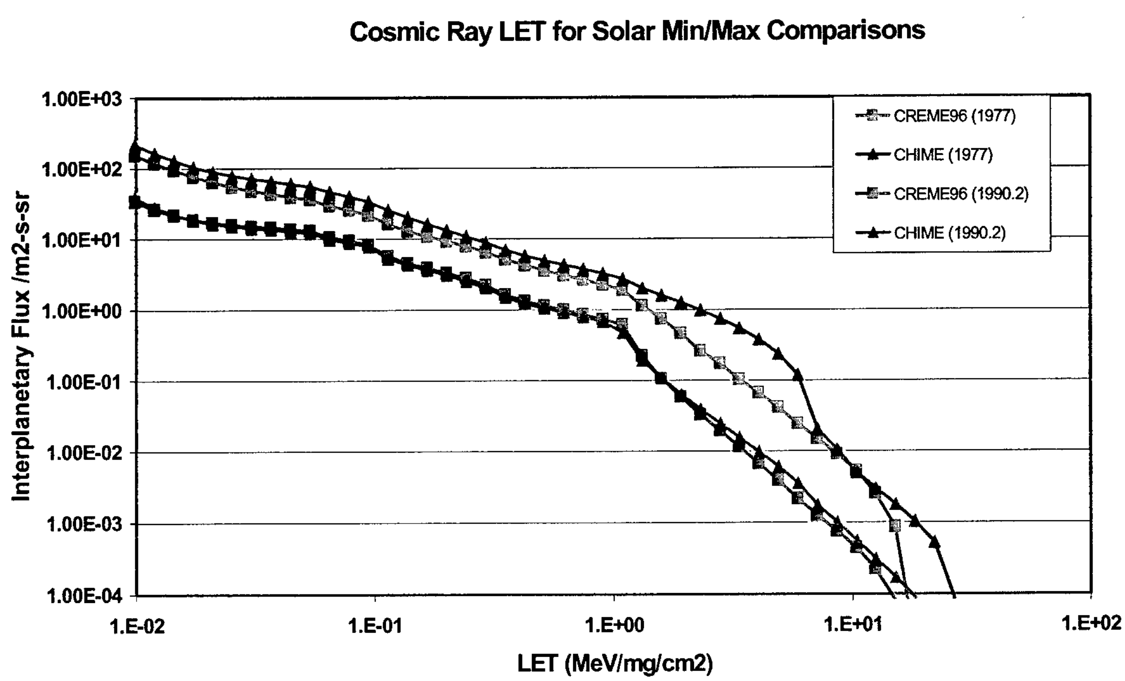

Figure 4. CREME96–CHIME Comparison of LET Spectra in Free Space for Solar Maximum (1990) and Solar Minimum (1977) Conditions

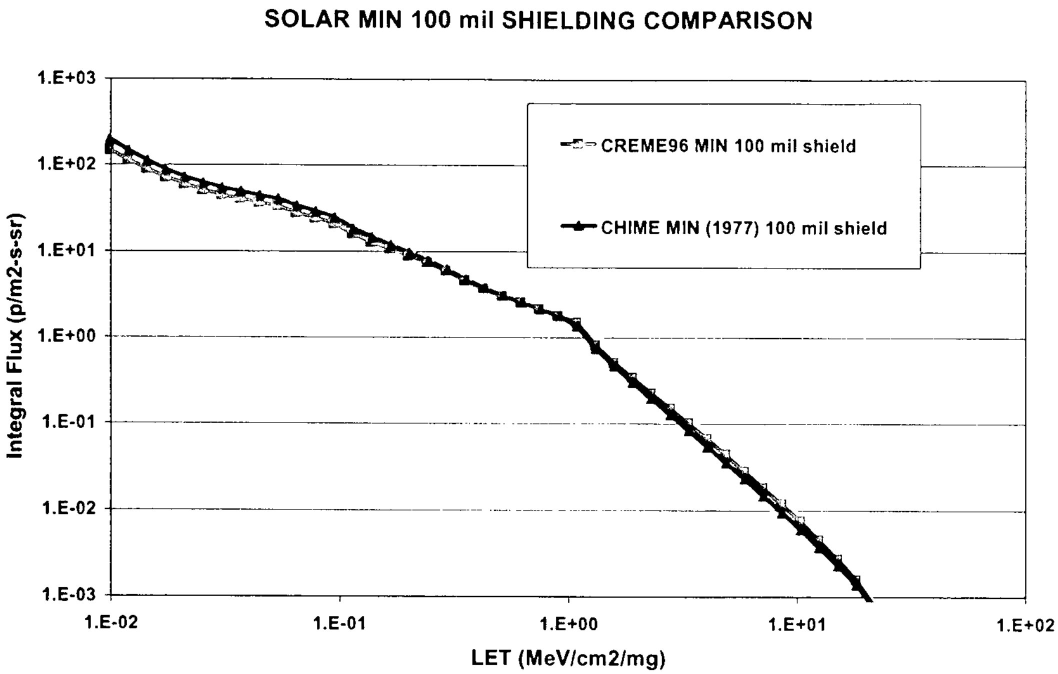

Figure 5. CREME96–CHIME Comparison (Solar Min LET Behind 100 mils Shield)

The experience from the DMSP program was that the background level of the highest LET particles in the polar regions was about 5 times larger than the background levels at low latitude outside the region of the SAA. (Mullen et al, AIP Conference Proceedings 186, 1989) Solar proton events can produce high proton background levels in the central polar cap regions, but they are usually short-lived with the peak fluxes seldom lasting longer than a single day. The LET spectrum for a LEO orbit for the peak flux values in the March 1991 solar particle event as run by CHIME), and the October 1989 event as run by CRÈME96 are shown in Figure 6. Figure 6 is a plot of the LET spectra unshielded and shielded with 100 mils for the two events. The shielding value is added to give a more realistic example of what the LET spectrum is at a device. The March event is higher at the lower energies and the October event is higher at higher energies. The shielding effectiveness is obviously greater for the softer spectra. Also included in Figure 6 are the same solar minimum and solar maximum LET spectra from Figure 4 to show the dominance of major flares for short periods. Remember these are peak spectra. For components highly susceptible to SEEs, cycling off for the flare periods is recommended.

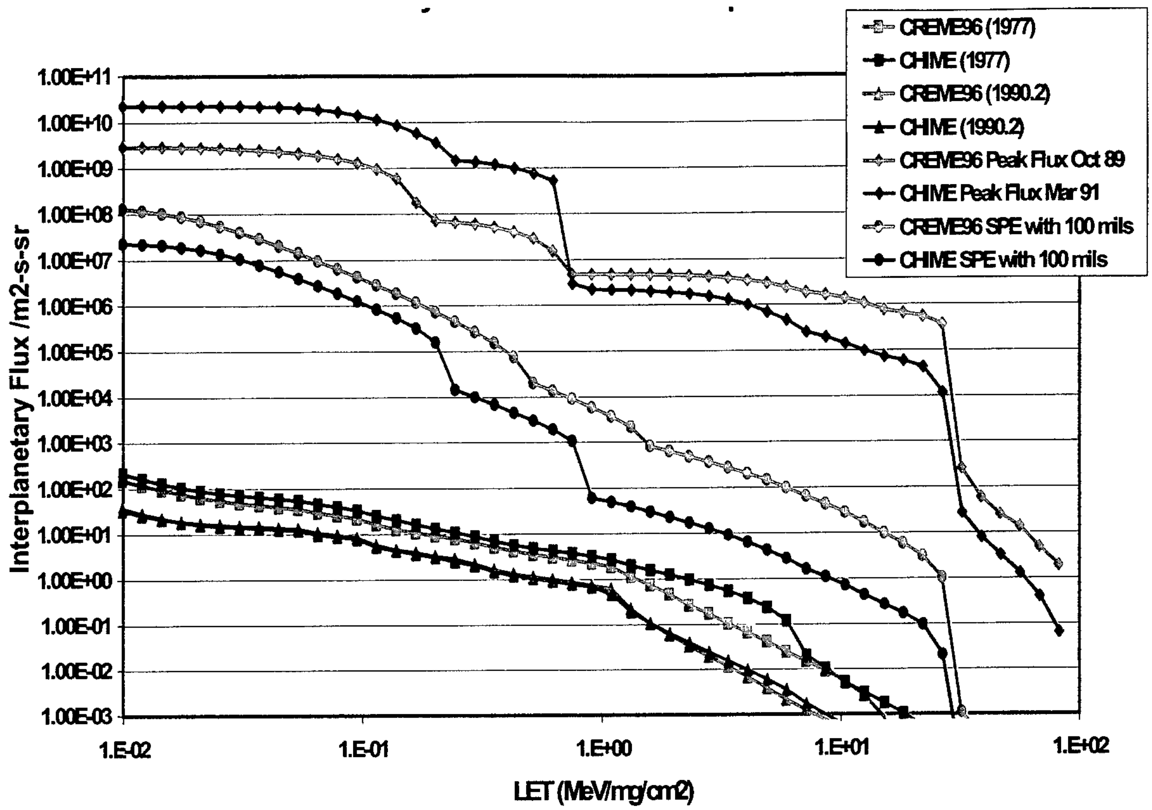

Figure 6. LET Spectra of the Major Solar Particle Events of March 1991 and October 1989 as Run Through CHIME and CREME96, in Free Space and with 100 mils Shield

3.4 SEE Characterization Tests

Test/flight devices that have elements susceptible to SEE should have testing performed to characterize their vulnerability to SEE. The keys to successful SEE testing are the test circuit hardware/software and the control capability of the proton/ion fluxes at the accelerator facility. The test circuit should be designed to measure all critical parameters of the structures under test with high accuracy. The circuit should also be able to carefully monitor current draw by the device, record it as a function of time, and be able to shut the device down before it burns up in a latch up condition.

Before going to an accelerator to characterize the device, it is useful to test the circuit, and get a general idea of the SEE vulnerability using a small radiation source such as Californium. After ensuring the test circuit is functioning as desired, full testing should be performed with both protons and heavy ions at the facilities most familiar to the test team. Data should be gathered at sufficient particle energies to obtain a cross-section versus LET curve from a few (2 or 3) MeV-cm^2/mg to over 80 MeV- cm^2/mg. A sufficient number of device structures should also be tested to get a statistically significant data base. Too small a sample can give misleading results if there is variation within a wafer and/or a wafer lot. A minimum sample size of 10 pieces with a control device is recommended. (Typically SEE tests don't use this many devices. However,

recently two separate groups performed SEE tests at the same facility with parts from the same fabrication lot. One saw latch-up and one didn't. One order was cancelled, one wasn't.)

Critical advanced technology devices such as those to be used for the focal plane array (if prone to latch-up and shown to latch below the desired LET level when tested), may be subjected to additional testing at a subsystem level with higher energy beams. There has always been some disagreement in the field that the typical SEE testing done with bare die does not truly replicate what happens in space, and over states the risk level for flying some devices. [This can be very expensive and I don't know what facilities are presently available.] There is experimental evidence from parts tested on the CRRES spacecraft that were known to latch at low levels in ground testing, and flown expressly to test latch-up in space with current protected circuits, and didn't latch on orbit over the satellite lifetime of 14 months. Risk levels for critical parts that have low latch-up thresholds can also be reduced by imposing operational constraints that are orbit and environment condition dependent. However, latch-up risk avoidance is always the preferred option.

3.5 SEE Operations Constraints

If it is decided that the program is willing to fly parts susceptible to non-destructive SEEs, operational tradeoffs can be made to turn sensitive systems or sensors off and on as the spacecraft moves in and out of the most hazardous regions for SEEs. Anywhere in near-Earth space there is a certain probability of upsets due to cosmic rays, but the most severe location for SEEs is in the heart of the inner proton belt for proton sensitive devices. During any major Solar Particle Event where the proton spectrum is hard, systems prone to SEE anomalies may also have to be disabled while in regions easily accessible by the SPE particles, such as the high-latitude polar regions and high altitude geosynchronous regions. (To date, I am not aware of any spacecraft anomalies due to SEEs in the polar regions, although several spacecraft have had SEE problems while passing through the SAA, to include DMSP and Hubble.) This would be for relatively few days over the mission lifetime since most SPEs have soft spectra. If turning instruments on and off periodically or aperiodically in orbit is considered a viable option, having the ability to store and send commands autonomously at pre-selected times on-board the spacecraft is highly desirable.

4. OTHER ENVIRONMENTAL FACTORS

As mentioned in the introduction other environmental factors may have to be added based on orbit selected, optical coatings, experiment susceptibility to EMI, etc. The other factors may include but not be limited to:

- spacecraft charging,
- cerenkov radiation light flashes,
- radiation induced optical coating discoloration,
- ion ram effects, and/or
- micrometeorite impacts.

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APPENDIX
SPECIFIC EXAMPLE OF A LEO SATELLITE TRADEOFF STUDY

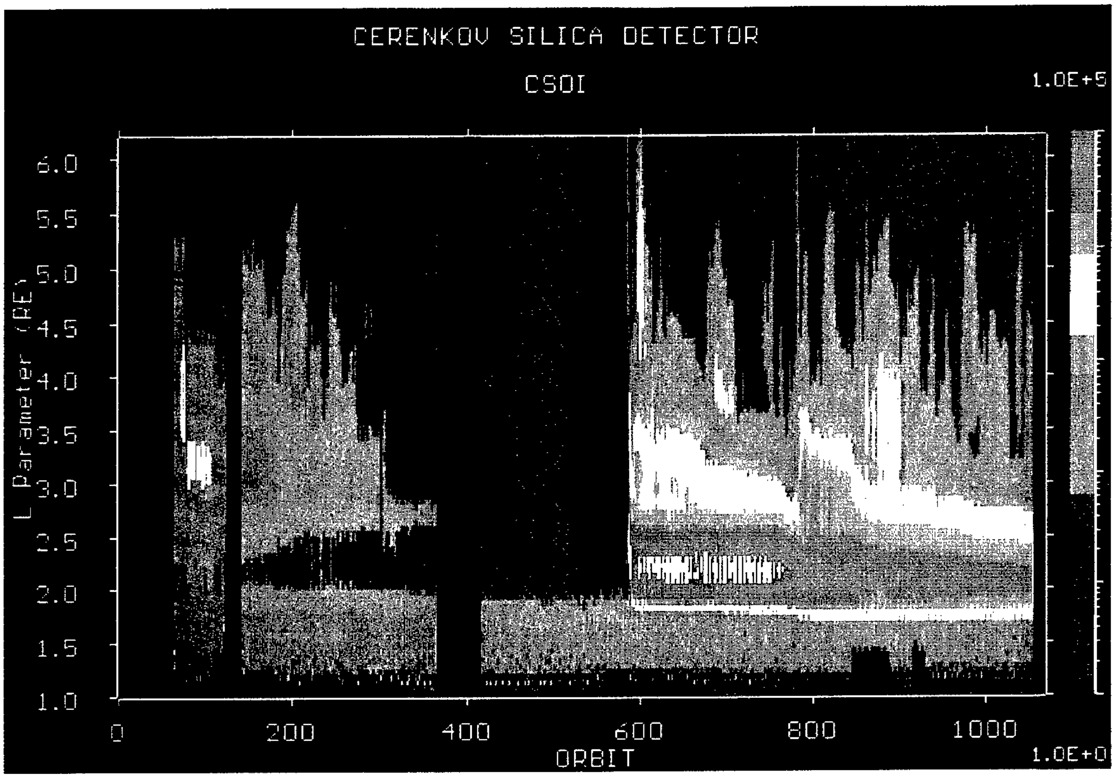
RADIATION CONSIDERATIONS FOR A LEO SATELLITE ARCHITECTURE STUDY

Abstract: The objective of this paper is to show how radiation levels vary in time and space for near-Earth satellite orbits. It contains the information needed to make an informed decision on radiation concerns for orbit tradeoff studies at Low Earth Orbit (LEO) altitudes.

Background: Satellites traversing LEO altitudes (here defined as altitudes between approximately 600 and 6000 nautical miles) encounter harsh proton and electron environments due to particle trapping in the near-Earth magnetic field. The main concerns for satellites at these altitudes are total dose degradation, dose rate effects, and Single Event Effects (SEE). Spacecraft charging at LEO for orbits less than 60° inclination is not a concern. Likewise, although low-level cosmic ray backgrounds exist in LEO orbits, they do not vary sufficiently over the LEO altitude range to warrant consideration for orbit tradeoffs. Four altitude ranges (600, 1000, 3000, and 5600 nautical miles) and 7 orbit inclinations (0, 10, 20, 30, 40, 50 and 60 degrees) are the primary focus of the study. The data bases for this study were provided by the USAF/AFRL at Hanscom AFB. These are the only known data bases that contain the information necessary to make informed decisions on the radiation environment over this altitude regime. For this study, the model dose values were directly measured behind 3 hemispheric domes of aluminum (82, 232, and 457 mils thick), and are reported as what would be observed over a hemispheric exposure. To get dose levels within a sphere of equivalent thickness, the values can simply be multiplied by a factor of 2. Since some of the figures are in units other than nautical miles, the following conversion factors are given: 600 nautical miles = 1111 km = 1.174 R_E (Earth radii); 1000 nautical miles = 1852 km = 1.291 R_E ; 3000 nautical miles = 5556 km = 1.872 R_E ; and 5600 nautical miles = 10371 km = 2.63 R_E .

LEO Radiation Dynamics: In steady state, the inner radiation belt for high energy protons extends from the top of the atmosphere in the region of the South Atlantic Anomaly to approximately 3500 to 4000 nautical miles. Protons with energies greater than 20 MeV produce most dose behind moderate shielding over this region of space. Somewhat higher dose levels from inner belt protons are expected during solar minimum, although there was little difference measured between solar minimum and solar maximum during the most recent solar cycle. Beyond approximately 5000-6000 nautical miles outer belt MeV electrons start to provide significant dose. The region between 3500 and 5000-6000 nautical miles is commonly termed the "slot region," since it is a region of minimum dose between a two-belt configuration of the magnetosphere. However, and it's a big however, about once to twice per solar cycle (on average) a major space storm occurs which can produce a belt of energetic electrons and protons in this slot region. This new belt produces more dose than in the heart of the inner belt for well-shielded devices. Figure A-1 gives a qualitative picture of what happens during one of these major storms. The two pictures (top and bottom) show altitude from the surface of the Earth (L=1 R_E) to near geosynchronous altitude (L=6.6 R_E) on the y-axis and the CRRES orbit number (10 hour geosynchronous transfer orbits) on the x-axis from launch in July 1990 to expiration in October 1991, a period of approximately 14 months. The color represents intensity level with a scale on the right side of each picture. The top picture shows multi-MeV electrons with energies between approximately 5 MeV and 30 MeV. (The instrument was not calibrated for these energies, since electrons at these energies were not believed to exist in sufficient numbers to

Multi-MeV Electron Counts



Total Dose Changes Behind 886 Mils Aluminum

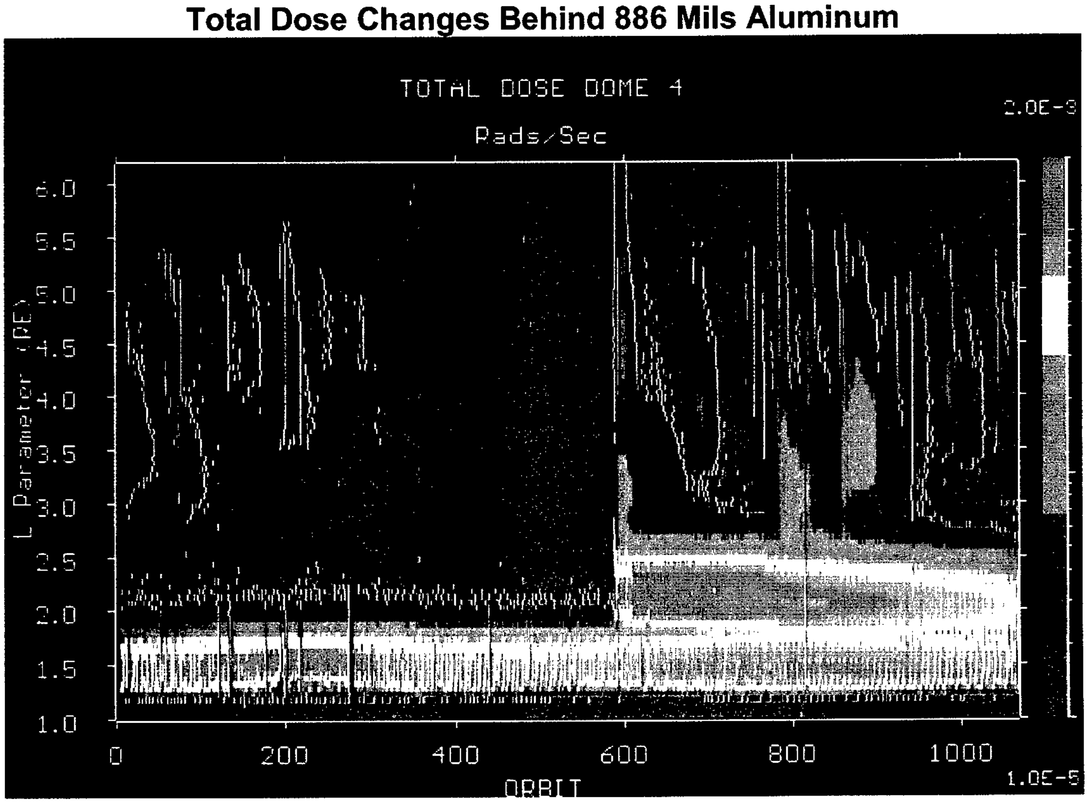


Figure A-1. New Belt Formation From The March 91 Storm

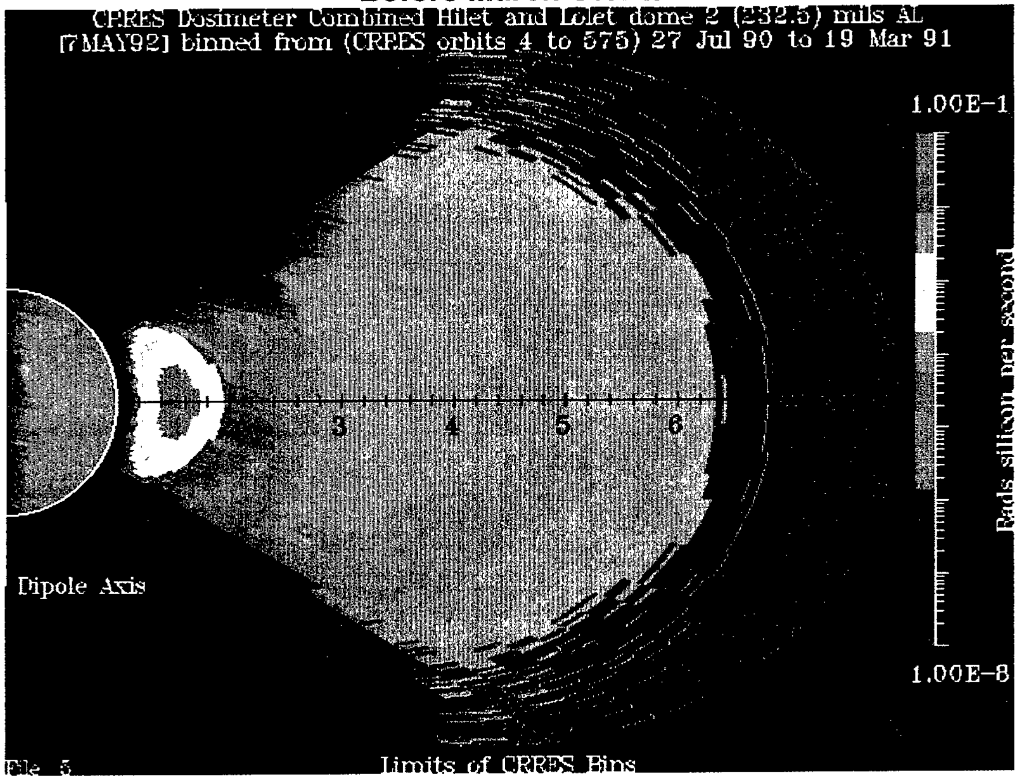
impact spacecraft.) The bottom picture shows dose rate behind 886 mils aluminum. What occurred near the end of March 1991 was a solar-induced major magnetic storm at the Earth which energized and moved the energetic protons and electrons into the normally benign slot region. The particles became trapped, producing a belt that gradually diminished over the 12 to 18 months. The figure clearly shows the peak intensity exceeding that of the inner belt, and the long duration of the trapping. This is the largest measured event to date, a smaller event was measured in February 1986 and data from a third event sometime around 1960 exists, although we don't know the size, date or duration of the ~1960 event. The events can occur anytime during the solar cycle and are unpredictable. The February 1986 event was near solar minimum and the 1991 event was near solar maximum.

Figure A-2 shows radiation maps for total dose rate levels behind a 232 mil aluminum dome before (top) the March 91 event and after (bottom) the March 91 event. Color represents intensity level. The plots are in magnetic coordinates to provide symmetry in data binning. The equator shown is the magnetic equator, which is 11° offset from the geographic equator. The horizontal scale is in R_E. The top picture shows the slot region and the bottom the slot filled in and providing dose for this thickness shielding (within the precision of the color scales used) equivalent to that of the inner belt.

<u>Orbit Specific Dose Values:</u> Dose values are calculated for each specific orbit in the study using the CRRESRAD dose model. Three shielding levels are given: 82 mils, 232 mils, and 457 mils of aluminum. The model outputs dose for 3 different time regimes: the total mission average dose, the average dose in the period before the March 1991 event, and the period following the March 1991 event. There is about a one week period during the event that is included in the total mission average dose but not in either the pre-March or post-March averages. This is to show the effects of a major solar particle event at geosynchronous altitude. Table A-1 gives the dose in rads/year for each condition of the study. At the lower two altitudes, the total dose is accented in blue to show that the event did not have any significant impact at these altitudes. For the higher two altitudes, the pre-event period is shown in green to signify a best case scenario, and the post-event case in red to signify a worst case scenario. As can be readily seen, the differences are dramatic. [Again, these numbers are for one hemisphere only.] Figure A-3 gives a plot of the 20° inclination doses for the three shielding levels (from the thinnest/top to the thickest/bottom) as a function of altitude. The blue curve is for the pre-event levels and the red curve for the post-event levels. Some intermediate points were added to give a better rendition of the curve.

<u>Single Event Effect Considerations:</u> SEE effects at these altitudes are primarily due to trapped protons. Relating actual SEE numbers to chips depends on many factors which are outside the scope of this study. What can be shown is the relative probability of upsets for devices susceptible to proton induced SEEs depending on orbit. The original maps were produced to determine operation scenarios for on-orbit space systems with known devices that upset. The maps are equally valuable for tradeoff studies. Figure A-4 shows the relative probability of upset contours at 600 (top) and 1000 (bottom) nautical miles. The white background level represents a probability of approximately .001 which is the cosmic ray background level that can create upsets anywhere in near-Earth space. The most intensive region in the two pictures represents a probability 2000 times that of the cosmic ray background level. It is obvious from the two pictures that the probability of upset is greater for lower inclinations in both cases, and the total

Before March Storm



After March Storm

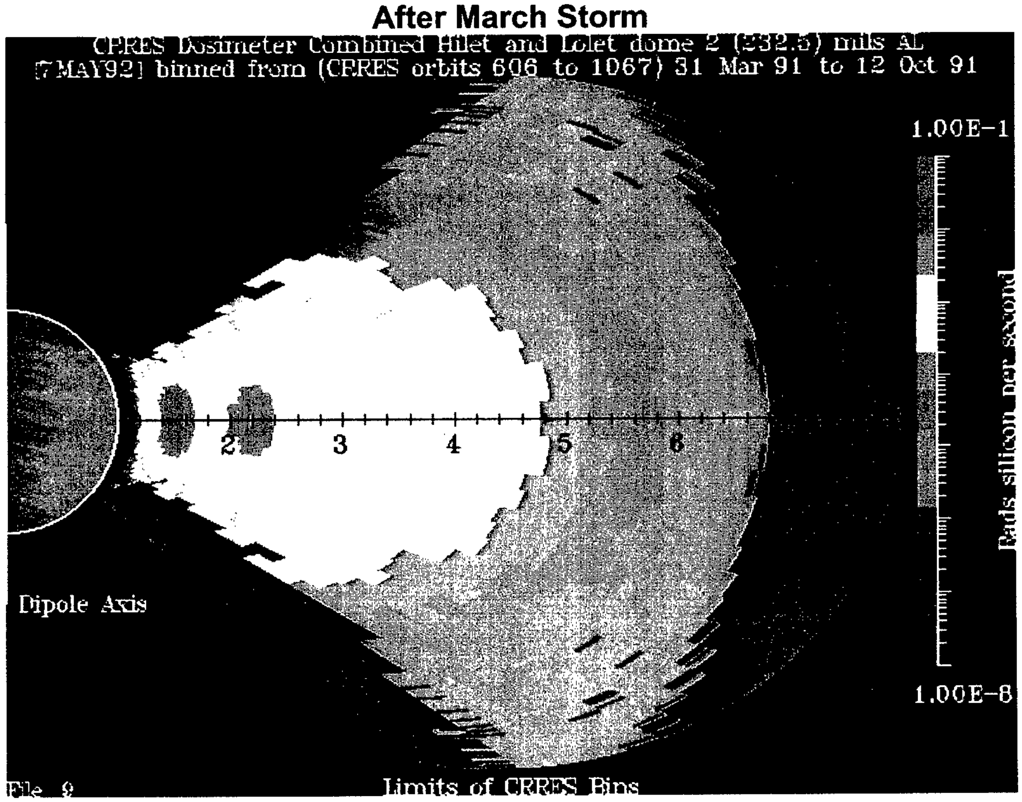


Figure A-2. Radiation Maps

Table A-1. Radiation Dose As A Function Of Altitude & Inclination

altitude (nmi)	altitude (km)	inc angle (degrees)	82 mils total (rads/year)	82 mils pre Mar (rads/year)	82 mils post Mar (rads/year)	232 mils total (rads/year)	232 mils pre Mar (rads/year)	232 mils post Mar (rads/year)	457 mils total (rads/year)	457 mils pre Mar (rads/year)	457 mils post Mar (rads/year)
600	1111	0	3367	3311	3399	2739	2759	2710	2585	2598	2571
600	1111	10	3353	3314	3397	2677	2701	2653	2516	2528	2511
600	1111	20	4123	4043	4190	3065	3088	3021	2831	2842	2809
600	1111	30	4203	4139	3795	2803	2823	2623	2535	2542	2422
600	1111	40	3457	3413	2898	2154	2168	1945	1917	1922	1783
600	1111	50	2542	2511	2145	1624	1636	1473	1454	1459	1357
600	1111	60	2145	2118	1845	1390	1400	1272	1248	1253	1173
1000	1852	0	48000	46000	49000	32000	32000	32000	29000	29000	29000
1000	1852	10	46000	45000	48000	30000	30000	30000	27000	27000	27000
1000	1852	20	42000	41000	42000	25000	25000	24000	22000	22000	22000
1000	1852	30	33000	32000	31000	18000	18000	17000	16000	16000	15000
1000	1852	40	25000	24000	22000	13000	13000	12000	11000	11000	11000
1000	1852	50	19000	18000	18000	10000	10000	10000	9000	9000	9000
1000	1852	60	17000	16000	16000	9000	9000	9000	8000	8000	8000
3000	5556	0	102000	[illegible]	[illegible]	27000	[illegible]	[illegible]	21000	[illegible]	[illegible]
3000	5556	10	89000	[illegible]	[illegible]	26000	[illegible]	[illegible]	21000	[illegible]	[illegible]
3000	5556	20	61000	[illegible]	[illegible]	21000	[illegible]	[illegible]	18000	4000	[illegible]
3000	5556	30	41000	[illegible]	[illegible]	16000	[illegible]	[illegible]	14000	2400	[illegible]
3000	5556	40	30000	[illegible]	[illegible]	11000	[illegible]	[illegible]	10000	2000	[illegible]
3000	5556	50	24000	[illegible]	[illegible]	9000	[illegible]	[illegible]	8000	1500	[illegible]
3000	5556	60	21000	[illegible]	[illegible]	8000	[illegible]	[illegible]	7000	1300	[illegible]
5600	10371	0	114000	[illegible]	[illegible]	23000	[illegible]	[illegible]	6000	200	[illegible]
5600	10371	10	157000	[illegible]	[illegible]	24000	1000	[illegible]	5000	200	10000
5600	10371	20	192000	[illegible]	[illegible]	20000	1300	[illegible]	4000	200	7000
5600	10371	30	169000	[illegible]	[illegible]	16000	1100	[illegible]	2500	100	5000
5600	10371	40	135000	[illegible]	[illegible]	11000	1000	[illegible]	2000	100	4000
5600	10371	50	98000	13000	[illegible]	9000	1000	[illegible]	1500	100	3000
5600	10371	60	83000	11000	[illegible]	8000	600	[illegible]	1300	100	2500

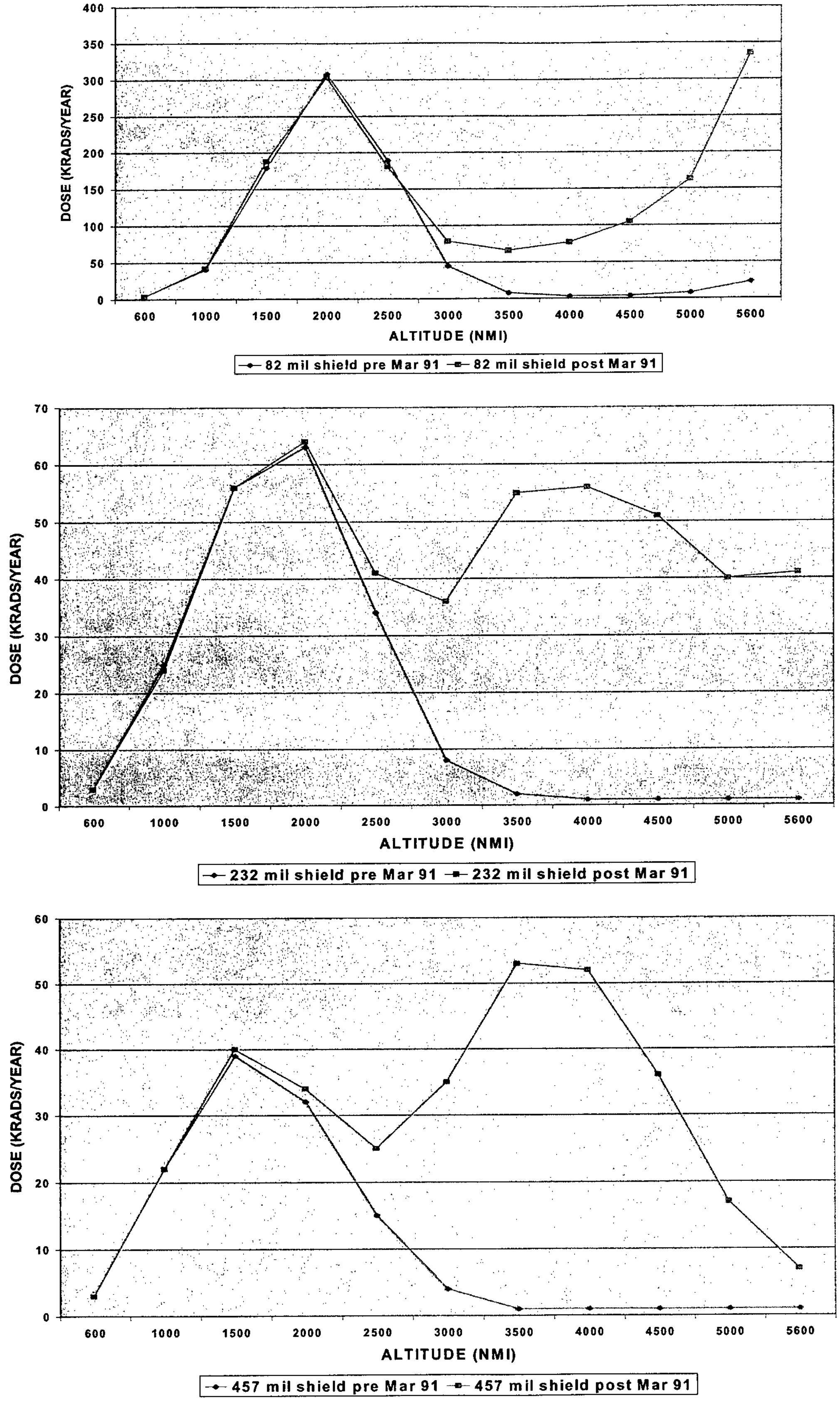
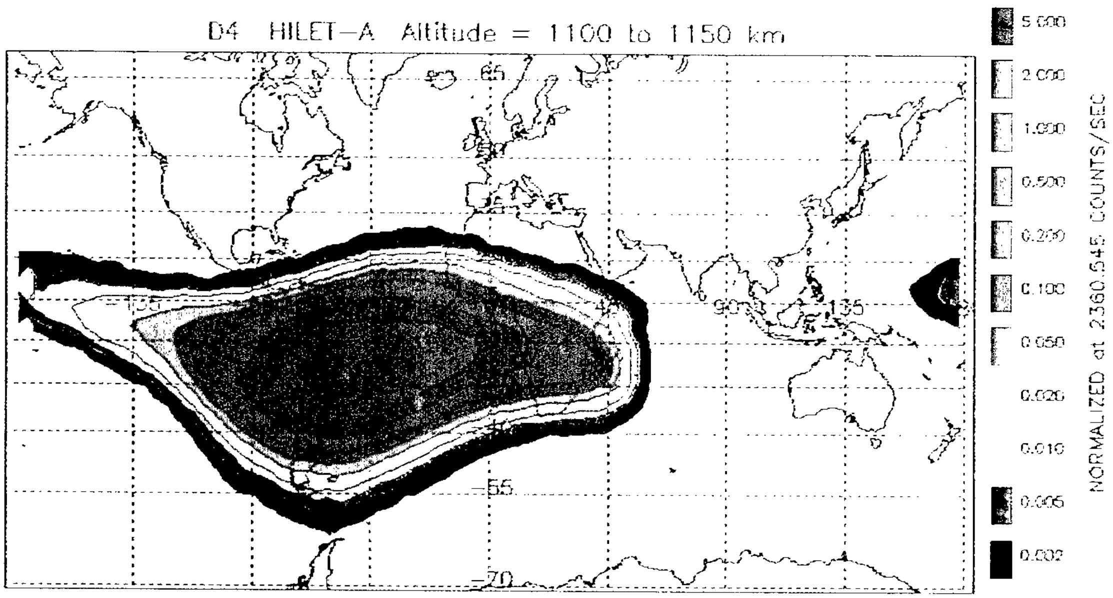


Figure A-3. Radiation Dose Versus Altitude For 3 Shielding Thickness (20° Inclination)

600 Nautical Miles



1000 Nautical Miles

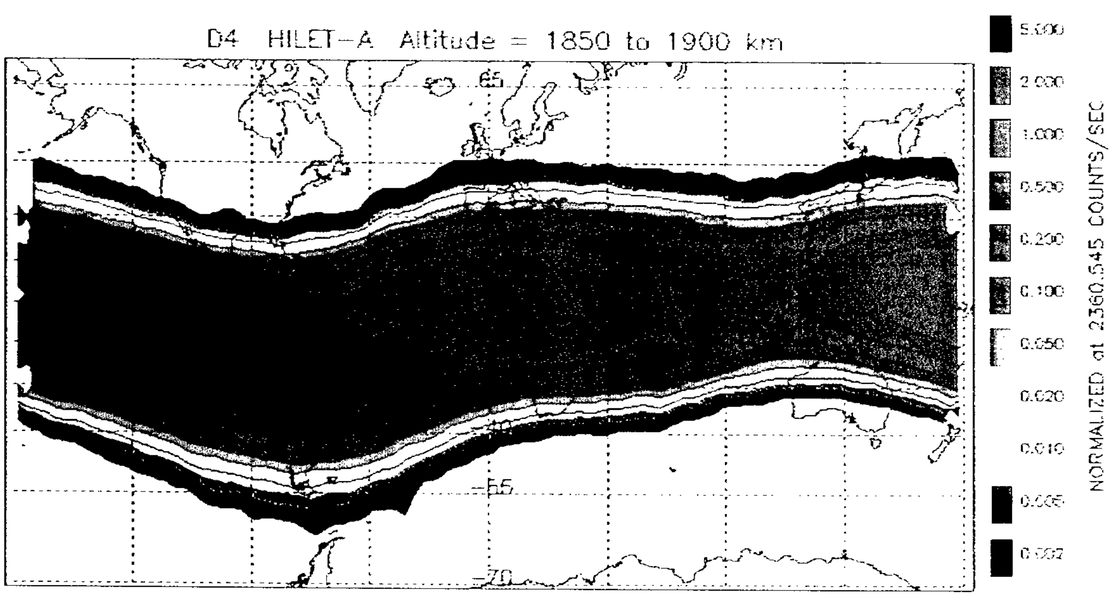


Figure A-4. Relative Probability Of SEUs Due To Protons

orbit probability is much higher at 1000 nautical miles than 600. At the highest altitude, 5600 nautical miles, the inner belt SEE causing protons are almost non-existent either before or after the event. At 3000 miles the probabilities are expected to fall somewhere between the 600 and 1000 mile cases in intensity, closer to the 600 mile level than that at 1000 miles. The actual maps will differ for pre- and post-event conditions. The 3000 nautical mile maps are not yet available, but are in development.

Summary: From the data presented here, it is shown that the lower two altitudes (600 and 1000 nautical miles) have well characterized radiation levels that remain nearly constant even under the most dynamic natural conditions. The upper two altitudes (3000 and 5600 nautical miles) on the other hand, experience radiation background levels that can change up to orders of magnitude depending on unpredictable solar influences. To date, there is no reason to believe that the large events that create high energy, intense belts occur more frequently than once per 10 years on average. (Not all major magnetic events create new belts.) But, our space data base is only spotty at best over 3 to 4 solar cycles, and we do not yet fully understand the physics of the processes that create these new belts at higher LEO altitudes.